REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden ... per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining ... of information. Send comments regarding this burden estimate or any other aspect of this collection of information ... Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite ... and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1994	Scientific Paper

4. TITLE AND SUBTITLE

PLGR Accuracy Evaluation

5. FUNDING NUMBERS

6. AUTHOR(S)

Daniel C. Oimoen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Topographic Engineering Center
ATTN: CETEC-PAO
7701 Telegraph Road
Alexandria, VA 22315-3864

8. PERFORMING ORGANIZATION REPORT NUMBER

R-226

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Personnel in the Corps of Engineers are authorized users of Precise Positioning Service (PPS) GPS. The Precise Lightweight GPS Receiver (PLGR) is the Army's authorized GPS receiver (Corps of Engineers personnel can obtain this). The U.S. Army Engineer School requested TEC evaluate the positional accuracies attainable with the PLGR. The evaluation covered four areas: real-time absolute, real-time differential, "post-processed" absolute, and "post-processed" differential. This paper discusses the techniques used and the accuracies observed. Capabilities, as well as limitations, of the current PLGR will also be discussed.

14. SUBJECT TERMS

Precise Positioning Service (PPS), PLGR, evaluation, accuracies

15. NUMBER OF PAGES

8

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and title page. Instructions for filling in each block of the form follow. It is important to ***stay within the lines*** to meet ***optical scanning requirements***.

Block 1. Agency Use Only *(Leave blank)*.

Block 2. Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

Block 3. Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

C -	Contract	PR -	Project
G -	Grant	TA -	Task
PE -	Program Element	WU -	Work Unit Accession No.

Block 6. Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. Performing Organization Name(s) and Address(es). Self-explanatory.

Block 8. Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. Sponsoring/Monitoring Agency Name(s) and Address(es). Self-explanatory.

Block 10. Sponsoring/Monitoring Agency Report Number. *(If known)*

Block 11. Supplementary Notes. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of...; To be published in.... When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. Distribution/Availability Statement. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR).

- **DOD** - See DoDD 5230.24, "Distribution Statements on Technical Documents."
- **DOE** - See authorities.
- **NASA** - See Handbook NHB 2200.2.
- **NTIS** - Leave blank.

Block 12b. Distribution Code.

- **DOD** - Leave blank.
- **DOE** - Enter DOE distribution categories from the Standard Distribution for Unclassified Scientific and Technical Reports.
- **NASA** - Leave blank.
- **NTIS** - Leave blank.

Block 13. Abstract. Include a brief *(Maximum 200 words)* factual summary of the most significant information contained in the report.

Block 14. Subject Terms. Keywords or phrases identifying major subjects in the report.

Block 15. Number of Pages. Enter the total number of pages.

Block 16. Price Code. Enter appropriate price code *(NTIS only)*.

Blocks 17. - 19. Security Classifications. Self-explanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

Block 20. Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.

PLGR ACCURACY EVALUATION

Daniel C. Oimoen
U.S. Army Topographic Engineering Center
ATTN: CETEC-TD-GS
7701 Telegraph Road
Alexandria, VA 22315-3864

BIOGRAPHICAL SKETCH

Daniel Oimoen is a civil engineer with the Surveying Division, Geographic Information Laboratory at TEC. He is responsible for the development and testing of Global Positioning System (GPS) surveying techniques. Mr. Oimoen has provided GPS training to surveyors of the US Army Topographic Engineer Battalions and the Corps of Engineers districts. Mr. Oimoen received Bachelors and Masters degrees in Civil Engineering (Surveying Option) from the University of Wisconsin--Madison. Prior to working at TEC, Mr. Oimoen served as a topographic engineer officer with the 30th Engineer Battalion (Topographic).

ABSTRACT

Personnel in the Corps of Engineers are authorized users of Precise Positioning Service (PPS) GPS. The Precise Lightweight GPS Receiver (PLGR) is the Army's authorized GPS receiver (Corps of Engineers personnel can obtain this). The U.S. Army Engineer School requested TEC evaluate the positional accuracies attainable with the PLGR. The evaluation covered four areas: real-time absolute, real-time differential, "post-processed" absolute, and "post-processed" differential. This paper discusses the techniques used and the accuracies observed. Capabilities, as well as limitations, of the current PLGR will also be discussed.

INTRODUCTION

The U.S. Army Engineer School requested TEC evaluate the positional accuracies attainable with the Precision Lightweight Global Positioning System (GPS) Receiver (PLGR). Based on current military survey tasks, these accuracies indicate to what extent the PLGR can be utilized by a military surveyor.

The evaluation primarily focused on the PLGR, as is. Four types of accuracies were examined: (1) real-time absolute, (2) real-time differential (relative), (3) "post-processed" absolute, and (4) "post-processed" differential. PLGR observed accuracies are shown in Table 1.

Further testing, in different environments (such as locations with higher ionospheric activity), is desired to determine if similar results can be obtained.

	Real-time	Post-processed	
Absolute	10 14	2-10* 3-14*	*Depends on amount of averaging time.
Differential	NOT TESTED	2 4	

Table 1. Summary of PLGR Accuracies (Horizontal on top, vertical below) at 95% confidence in meters.

WHAT IS PLGR?[1]

PLGR is the Army authorized GPS receiver for tactical operations. It is a 5-channel L1 C/A, P, and P(Y) code hand-held GPS receiver. Five satellites can be continuously tracked, but the four "optimal" satellites are used for the position computation. PLGR outputs position, velocity, and time information. When "keyed", PLGR will operate in any "GPS environment"; the keys enable PLGR to negate the effects of selective availability (SA) and provide anti-spoofing (AS) capability. This is referred to as the Precise Positioning Service (PPS). Several non-DOD government agencies are exploring the possibility of establishing a Memorandum of Agreement with DOD to obtain authorization to procure PLGR or other PPS receivers.

The specifications for PLGR are given below:

Horizontal	10 meter (CEP, 50%)
Vertical	10 meter (VEP, 50%)
3-D	16 meter (SEP, 50%)

Capabilities

PLGR was designed to act as a stand-alone positioning and navigating device. PLGR horizontal positions can be referenced to a user-selectable datum (including NAD27 and NAD83). PLGR can output positions in Latitude and Longitude or Universal Transverse Mercator (UTM). It has a RS-232 communications port for interfacing to other devices, and it can store up to 99 waypoints internally. PLGR has the capability of user-selecting/deselecting individual satellites. For horizontal positioning requirements on the order of 10-20 meters, a PPS receiver such as PLGR, that requires no communication link or post-processing is an option.

[1]PLGR refers to the actual DOD PPS hand-held GPS receiver; other manufacturer's PPS GPS receivers will have other capabilities/limitations.

Limitations

Below are some limitations of the current version of the PLGR. A user can NOT input a desired elevation mask into the PLGR; PLGR may select satellites at any elevation angle. PLGR outputs positions but does NOT output raw observables (such as pseudo-range and carrier phase information); therefore, many of the data processing functions performed on data from commercial GPS receivers are NOT possible with the current PLGR. Because it does not record raw observables, data from PLGR can not be written into a RINEX file format for post-processing with data from a reference station. If unkeyed, PLGR can receive C/A code differential corrections. Currently, however, it requires a computer with the appropriate hardware and software to receive RTCM SC 104 Type 1 and 2 messages, reformat them, and then send them to the PLGR. There is no easy way to switch between keyed (PPS) and unkeyed (SPS) modes. The interface protocol for communicating with the PLGR is a proprietary format; it does NOT provide output data messages such as those for NMEA0183.

PLGR ACCURACY TESTING

Testing primarily took place in the vicinity of Fort Belvoir, Virginia. For long-range differential testing, sites at Fort Belvoir, VA and Fort Monmouth, NJ were used. Initial data collection began in August, 1993 with pre-production PLGRs. An eight day absolute GPS data collection session was conducted from August 31, 1993 to September 8, 1993. Relative GPS data were collected between October, 1993 and January, 1994. All testing was conducted with "keyed" PLGRs.

Statistical Terms

No measuring system can measure perfectly; a system normally has an accuracy and probability statistic stated for it. The probability statistic indicates the level of confidence (probability) that any random measurement will be accurate to within the stated accuracy. PLGR specifications use statistics which are based on a normal distribution of measurements with no systematic biases. PLGR specifications use the 50% probability statistic: CEP for horizontal, VEP for vertical, and SEP for 3-D positions . This means that 50 percent of the time PLGR should provide positions to better than 10 meters, horizontally. Often times, 90 percent or 95 percent probability statistics are used. As a rule of thumb, to convert a 50 percent probability statistic for normally distributed data to a 95 percent probability statistic use the formulas:

(1-D) VEP x 2.9 = 95%
(2-D) CEP x 2 = 95%
(3-D) SEP x 1.8 = 95%

Therefore, a PLGR with good satellite geometry should compute horizontal positions to better than CEP x 2 (10 x 2) = 20 meters 95 percent of the time.

Real-time Absolute

This is the mode that most Army users of PLGR will employ. It is primarily intended for navigation purposes. One receiver, stand-alone, determines a position directly on the WGS84 datum. The specifications listed before are for this mode of operation; the specifications also assume a good satellite geometry (see Figure 1).

In the 2-D example, good geometry (low Dilution of Precision, DOP) occurs when the area of the triangle formed between the GPS receiver and the two satellites is a maximum. Geometric DOP (GDOP) relates to the geometry of the four satellites being used in the position computation. Theoretically, the lower the GDOP value, the better the accuracy of the position. The elevation angle of the satellites can also impact the accuracy attainable. Range measurements from satellites very low on the horizon (0-3 degree elevation angle) may have larger errors which result in not-so-accurate positions.

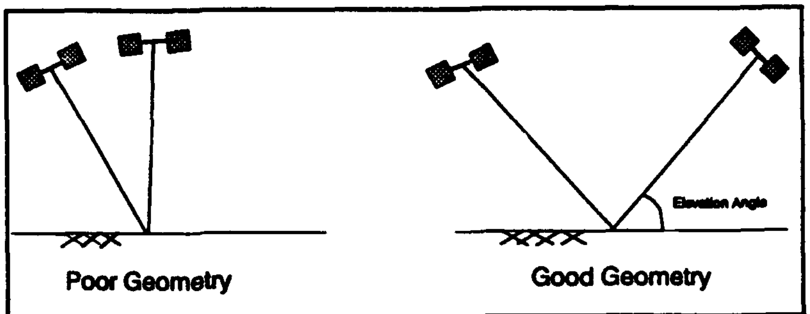


Figure 1. Simplified 2-D example of satellite geometry.

Appendices 1 and 2 show the real-time accuracies attained with PLGR. The first 30 trials in Appendices 1 and 2 were with good geometry (PLGR displayed an accuracy indicator of +/- 10 meters). Trials 31-60, 61-90, and 91-120 were when PLGR reported +/- 20 meters, +/- 30 meters , and +/- 40 meters. Note that in the first 30 trials, on two occasions even though PLGR indicated +/- 10 meters, the error was more than 15 meters. In these cases, several satellites were at elevation angles below three degrees.
Under good satellite geometry conditions, PLGR easily exceeds specifications. For a sample of more than 10,000 positions computed from good geometry conditions in "CONTINUOUS" mode, accuracies were on the order of 5 meters (CEP and VEP). PLGR operating in a "QUICK FIX" mode was not directly tested. Soldiers will sometimes be in terrain where optimal satellite geometry is not possible. Be aware of the accuracy indicated by PLGR--it will NOT always be optimal (within 10 meters)!

Real-time Differential

Real-time differential GPS involves at least two GPS sets: one over a "known" reference control station and at least one "roving" to other points of interest. For real-time operation, a data communication link from the control station to the roving stations is required. Basically, the known station computes corrections to its position computation (between what is measured and what its known values are) and then transmits those corrections for the roving stations to use for a better position

computation. There are two common ways to generate these corrections: pseudo-range corrections (PRCs) and delta positions.

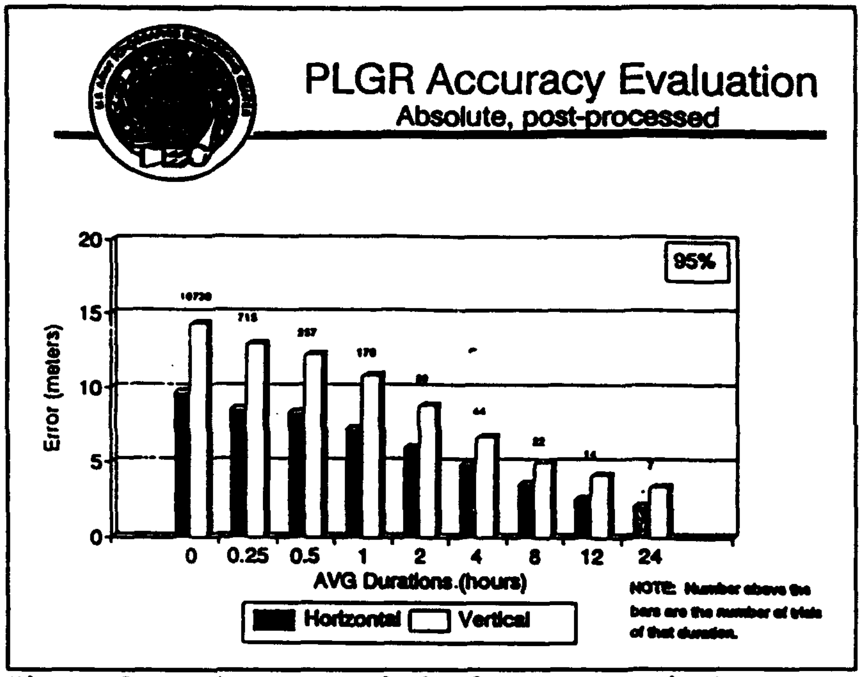


Figure 2. Post-processed Absolute (Averaging).

Corrections by PRCs is the preferred method. A pseudo-range is the raw range (distance) from a satellite to the GPS receiver. At the control station, PRCs are computed by differencing the measured raw pseudo-range and the known true range (for each satellite). The PRCs are then transmitted to the remotes where the PRCs are applied to the remote's pseudo-ranges to obtain better range measurements. Corrected range measurements are then used for a better position computation. PRCs are more flexible from an operational perspective; RTCM formats for real-time differential GPS are based on PRCs.

Transmission of classified encrypted Y-code PRCs is not an option with the current PLGR; therefore, PLGR can only operate in a real-time differential mode (following RTCM standards) by using C/A code. In addition, PLGR can act as a rover (it can receive C/A code PRCs) but NOT as a reference over a known control station (it can NOT generate PRCs). Because the C/A code is not encrypted, it is not authorized for tactical operations; therefore, real-time differential GPS with C/A code is not authorized for tactical operations. Because we "Train as we fight...", real-time C/A code differential GPS was not tested.

Commercially available real-time C/A code differential GPS vendors often quote 3-5 meter relative horizontal accuracies over ranges of several hundred kilometers. Commercial systems using a combination of C/A code and carrier phase information have obtained sub-meter relative accuracies in real-time. New "on-the-fly" GPS systems will use code and carrier information to obtain centimeter level relative accuracies in real-time. Commercially available GPS receivers can use the code and carrier information to obtain these accuracies; PLGR can NOT.

Post-processed Absolute

Post-processed absolute is an averaging of real-time absolute positions over some time interval (one receiver, stand-alone).

In the case of the PLGR, this is simply an arithmetic mean of position computations over time. Two of the main considerations in averaging are time interval and satellite geometries.

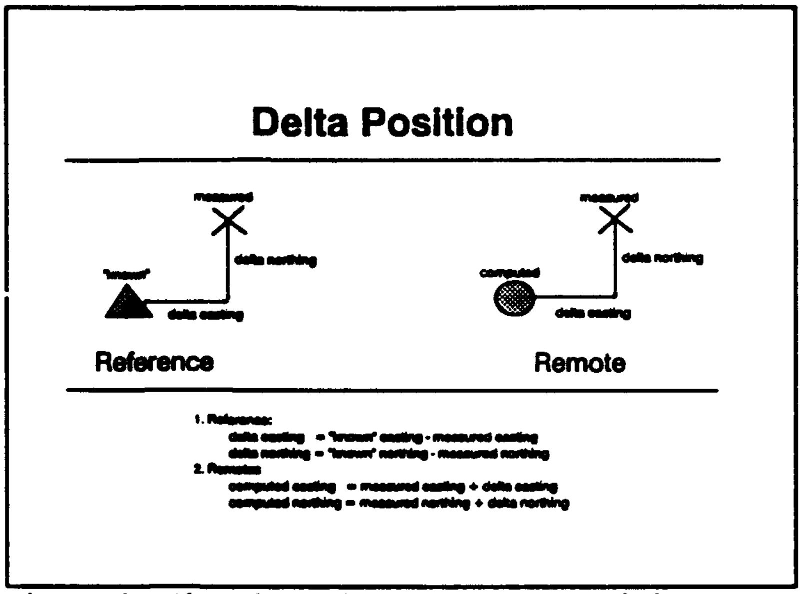


Figure 3. View from above of delta position differential GPS.

At TEC, continuous PLGR data were collected over an eight day period. This data set could be segmented and examined as separate data sets; this enabled us to look at five minute averaging durations, one hour durations, four hour durations, and so on. As shown in Figure 2, positional accuracies improved over time. For 24 hour sessions, absolute positional accuracies were on the order of 3 meters (95 percent confidence). For a one hour averaging duration, absolute positional accuracies were on the order of 7 meters, horizontally (95 percent confidence). It is interesting to note how satellite geometry affects these results. Averaging with the same constellation over time did not improve accuracy. Same constellation averaging accuracy for one hour did not show any significant improvement over five minutes. Averaging with the same constellation gives the appearance of a systematic bias. To try to randomize this bias and improve accuracy, multiple complementing satellite geometries are required. This happens automatically when averaging for durations longer than an hour. Further testing is being conducted to determine if software can reduce the observation time required to obtain multiple complementing satellite geometries from hours to minutes.

For vertical, PLGR outputs either an ellipsoid height (h) or a mean sea level, MSL, height (H). The MSL is derived from h by the following formula:

$$H = h - N$$

The geoid undulation (N) is selected from a geoid model. PLGR uses a 10° x 10° geoid model. For best results with the vertical, a user should average with ellipsoid heights and then use a better geoid model (such as GEOID93) to convert it to a MSL (H) height.

Post-processed Differential

Whereas real-time differential requires a communication link, post-processed differential does not. Data from the reference

and remote GPS receivers are combined and processed. Again, differential requires one reference GPS set to be over a "known" control station to compute corrections.

As discussed in the "Real-time Differential" section, differential GPS using PRCs in a tactical area is not an option with PLGR; therefore, it was not tested. Corrections by delta positions are possible with PLGR. This method computes corrections to the actual position computation at the "known" control and applies the "delta positions" to the position computations for the rovers (see Figure 3). Several conditions **MUST** be met for this technique to be valid. These consist of the following:

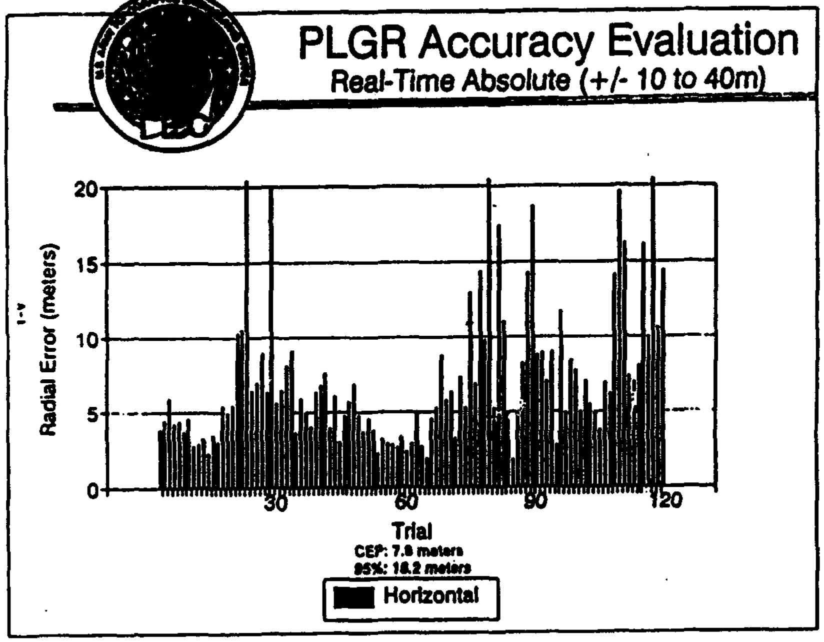
1. Reference GPS receiver and remote GPS receivers **MUST** use the same position computation algorithm.
2. For PLGR, reference and remotes **MUST** use the same four satellites in the position computation.
3. Positions **MUST** be computed for the same times.

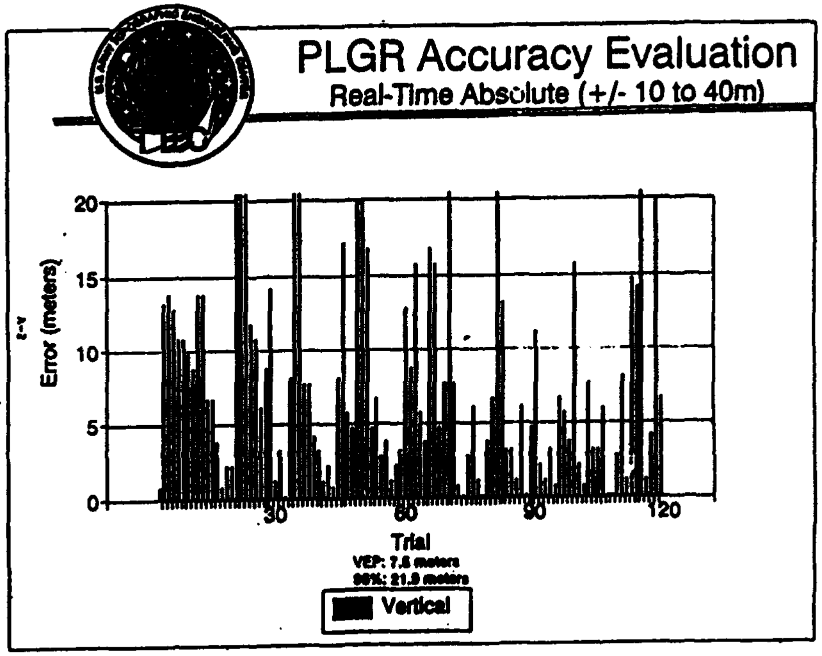
This technique has been applied over baselines ranging from 10 meters to 300+ kilometers. Relative accuracies on the order of 2 meters, horizontally, and 4 meters, vertically, have been obtained. Appendices 4 and 5 show the results of these tests.

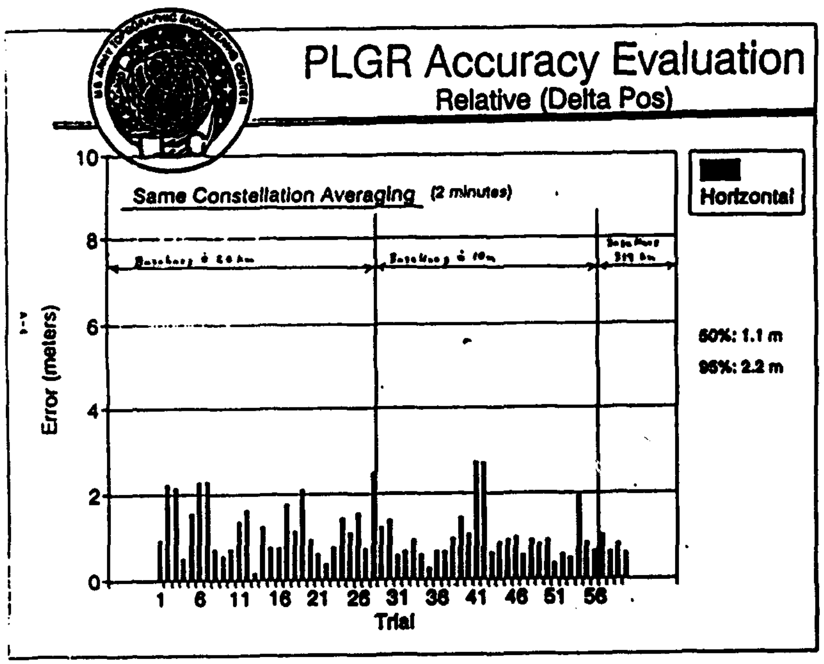
RECOMMENDATIONS AND CONCLUSIONS

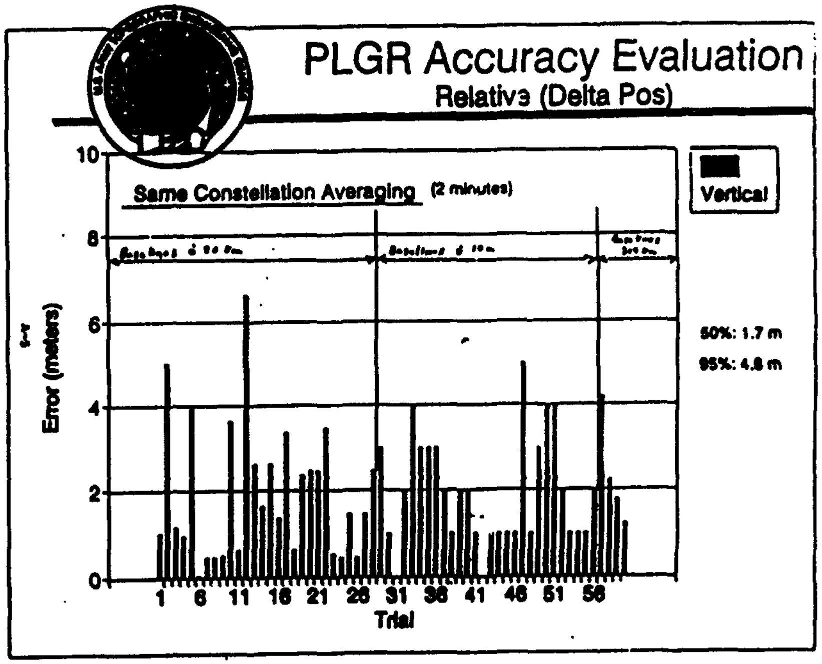
1. Further testing, in different environments (such as locations with higher ionospheric activity), is desired to determine if similar results can be obtained.

2. Cost of PLGR under the DOD contract will be around $1500; delivery time may exceed one year. With DOD approval, other PPS receivers can be procured. Cost of comparable PPS receivers are approximately $4500; delivery time may be several months. For some applications, PPS GPS may be the right tool.


PLGR Accuracy Evaluation
Real-Time Absolute (+/- 10 to 40m)
Radial Error (meters)
20
15
10
5
0
30
60
90
120
Trial
CEP: 7.9 meters
95%: 18.2 meters
Horizontal


PLGR Accuracy Evaluation
Real-Time Absolute (+/- 10 to 40m)
Error (meters)
20
15
10
5
0
30
60
90
120
Trial
VEP: 7.6 meters
95%: 21.9 meters
Vertical


PLGR Accuracy Evaluation
Relative (Delta Pos)
Same Constellation Averaging (2 minutes)
Horizontal
Error (meters)
10
8
6
4
2
0
1
6
11
16
21
26
31
36
41
46
51
56
Trial
50%: 1.1 m
95%: 2.2 m


PLGR Accuracy Evaluation
Relative (Delta Pos)
Same Constellation Averaging (2 minutes)
Vertical
Error (meters)
10
8
6
4
2
0
1
6
11
16
21
26
31
36
41
46
51
56
Trial
50%: 1.7 m
95%: 4.8 m